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HYDROGEN IN THE SUBCRITICAL AND SUPERCRITICAL
PRESSURE REGIMES OVER A RANGE OF ACCELERATIONS**

by Robert W. Graham, Robert C. Hendricks, and Robert C. Ehlers
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TECHNICAL PREPRINT prepared for Cryogenic Engineering
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ABSTRACT

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Pool heating of liquid hydrogen in the subcritical and supercritical pressure states has been investigated at earth gravity and multigravities. Acceleration does influence the incipience of nucleate boiling but does not affect established nucleate boiling. The film boiling heat transfer is influenced by multigravity accelerations.

A boiling-like mechanism was evident for hydrogen in the supercritical and near-critical state. Acceleration magnitude influenced the heat transfer in this fluid regime.

AUTHOR

INTRODUCTION

Pool heating of cryogenic fluids, and particularly liquid hydrogen, can be encountered in numerous space-vehicle-design applications. Such a vehicle may experience a variety of body accelerations which can range from zero gravity to 10 or more g's. Consequently, information on the manner in which the local gravity influences heat transfer is needed. In addition, the observed gravitational effects on the heat transfer of any fluid are useful in evaluating conceptual models of such processes as nucleate and film boiling.

A limited amount of heat-transfer data for the pool heating of liquid hydrogen appears in the literature (refs. 1 to 3). The pool boiling of

many fluids other than hydrogen is extensively reported in the literature. Several well-known correlations for predicting pool-boiling heat-transfer rates have been proffered (ref. 4). It cannot be assumed a priori that these correlations can be applied to boiling hydrogen.

In the boiling regime, several investigations have been made concerning the effect of gravity on the mechanism of boiling. Siegel and Usiskin (ref. 5) conducted an experiment with water at zero or near-zero gravity. Similar experiments with hydrogen and nitrogen were reported in references 1, 6, and 7 for the low-gravity condition. Several investigators have studied boiling and burnout in multigravity conditions (refs. 8 to 12), but none of these experiments have been with hydrogen.

The object of the experiments in this report was to assess the effects of multigravity on both the boiling and supercritical heating of liquid hydrogen. Measurements comprised: (1) energy into the heater, (2) heater surface temperature, and (3) bulk hydrogen temperatures and pressures. High-speed photographs including shadowgraphs of the fluid during heating were taken. The high-speed movies were valuable in gaining insight into the mechanisms of heat transport.

APPARATUS AND PROCEDURE

Apparatus

Figure 1(a) is a sketch of the 4-foot-arm centrifuge used to impose the varying multigravity acceleration forces on the fluid. The centrifuge was rotated by an air turbine, and the speed was measured by using an electronic frequency counter. The mounting of the tank and high-speed motion-picture camera at the end of the arm is schematically shown in figure 1(a).

The tank and the heating element are shown in figure 1(b). The tank volume was approximately 2 quarts and was equipped with observation and illumination windows for the photography. The tank was mounted on a free-rotating trunnion arrangement (see fig. 1(a)) that automatically enabled the tank-heater assembly to be oriented so that the resolved acceleration vector (gravity plus centrifugal) was perpendicular to the heater surface.

The tank was constructed as a Dewar in order to contain the liquid hydrogen. The inner tank that actually held the hydrogen was insulated with spaced laminations of aluminum foil. A vacuum was continuously maintained in the void regions between the layers of foil. As is shown in figure 1(a), the vacuum pump rotated with the arm to maintain this vacuum. Provision was made for pressurizing the Dewar and controlling this pressure to some preset value. A bleed line, as well as a pressurizing line, was required to make this possible. The bleed line was connected to an atmospheric vent that rotated with the apparatus. A strain-gage transducer was used to measure the tank pressure.

Heater

A cross-sectional view of the heater block and its associated surface temperature instrumentation is shown in figure 1(c). The heating ribbon was a thin Chromel-A ribbon mounted on a bakelite block. The ribbon was tension-mounted with springs on each end and was cemented to the surface of the bakelite block. The purpose of the tension mounted was to prevent buckling of the strip when it expanded during heating. By virtue of this mounting, the ribbon heated the fluid from one side only. The cross-sectional area of the ribbon was very uniform from end to end; thus it

was assumed that a uniform heat flux was developed over the entire heater length by resistive heating.

Considerable difficulty was incurred in developing a thermocouple system that would measure the surface temperature of the heater reliably. The hydrogen pool was used for the cold junction. The small temperature difference in nucleate boiling made precise measurement difficult. A thermocouple seemed to be the only instrument that would measure the local surface temperature at a very small contact area. Chromel-constantan was chosen as the thermocouple material because it provides approximately 50 percent greater electromotive force output than does copper constantan, and the junction is easy to spot weld.

As is shown in figure 1(c), three thermocouples were spotted on the back surface of the heater ribbon; this was done to minimize any surface changes provoked by the couple mountings. An appreciable error in actual surface temperature would be incurred, but this was preferred to any alterations in surface conditions that could drastically affect the boiling characteristics of the surface. To minimize the conduction of heat away from the thermocouple junction through the leads, 1/2-mil (0.0005 in.) thermocouple wire was used. This small size wire aggravated the installation problem. As mentioned earlier, the heater thermocouples indicated a temperature difference between the metal temperature and the hydrogen pool; the pool temperature was measured with two carbon resistor probes. The thermocouple output was then amplified by differential amplifiers isolated from common ground, hundredfold for the nucleate-boiling study and sevenfold for the film-boiling portions.

Before this thermocouple system (thermocouples, cold junctions, and amplifiers) was evolved and adopted, there were many hours of preliminary running to check out the system. It was anticipated that the slip rings might introduce some error into the temperature measurements, so tests were run in which the slip rings were by-passed, and these results were compared with spinning and nonspinning runs involving the slip rings. No slip-ring effect was noted. In fact, the entire instrumentation was evaluated in this process to avoid slip-ring errors. The remaining instrumentation, not mentioned thus far, include voltage taps and current leads on the heater ribbon for heater electrical power and a counter to indicate the rotational speed of the centrifuge.

Recording Devices

A digital potentiometer or an oscillograph were employed in gathering the data reported herein. All of the basic measurements including pressure and temperature, as well as electrical energy, were transduced to electrical outputs. For most of the running, the digital potentiometer recorded these outputs. Some of the runs, however, were recorded on an oscillograph, principally those involving high driving temperatures as encountered in film boiling and heating of supercritical hydrogen.

Precision of Measurement

An overall estimation of the precision of the data recording is difficult to make. The recording instruments themselves were of high precision; the digital potentiometer is rated as a 1/4-percent instrument. The bulk temperatures and pressures of the saturated hydrogen pool were compared with NBS data for para-hydrogen. For some of these

checks both a platinum and a carbon resistor probe were used. Some deviation from the NBS data was observed. The maximum error in bulk temperature was approximately 2 percent (0.5° to 1° R absolute error.) Some of this error might be attributed to the presence of superheated liquid as the result of heat leak through the tank walls, windows, and instruments leads.

It is estimated that the overall accuracy of measurement falls somewhere between 1 and 2 percent. This represents an integrated judgment of the precision of the data-taking system.

PROCEDURE

In general, the procedure was to study first the high-speed motion pictures and heat-transfer data obtained from a heater ribbon in ordinary gravity. Then the multigravity experimentation was programed, making sure that comparable thermodynamic conditions to those experienced at 1 g were attained. Generally, a multigravity and a 1-g experiment were run consecutively for the most meaningful comparison.

As the reader might surmise, operation of the facility at multigravity conditions was appreciably more difficult than at ordinary gravity. It was much more difficult to hold thermodynamic conditions steady in the Dewar.

Generally, the procedure for getting the multigravity data was identical for the subcritical and supercritical pressure states. The centrifuge rotational speed was set at a predetermined value and the heat flux to the heater ribbon was varied over a number of power increments. The experimental conditions covered included

Hydrogen pressures, lb/sq in. abs 50 to 260
 Hydrogen temperatures, °R 45 to 70
 Heat flux, Btu/(sec)(sq in.) up to 20
 The accelerations studied varied from 1 g to approximately 10 g's.

RESULTS

Comparison of Heating Curves for Subcritical and Supercritical Pressures

The multigravity effects can be assessed by comparing this level with comparable 1-g data. Unless otherwise specified, all of the local-heat-transfer data reported herein are for the center station of the heater block. This selection would tend to eliminate end effects that could influence the two extreme stations.

Figure 2 shows the heating curves for hydrogen obtained with the heater block shown in figure 1(c) in both the subcritical and supercritical pressure regimes in an Earth-gravity environment (gravity vector normal to the heater surface). These are the temperature differences recorded by the center thermocouple located on the bottom surface of the heater strip. Because of the finite thickness of the heater, a temperature gradient would exist across the thickness of the strip. The dashed curve in the nucleate portion (A) of figure 2 is an estimated correction based on a one-dimensional conduction calculation. The correction is significant at the upper end of the nucleate-boiling curve. The correction may not be accurate, however, because the thermal conductivity for Chromel-A is not known at cryogenic temperatures and heat leak into the bakelite block or through the thermocouple leads was not considered.

In general, figure 2 looks quite similar to comparable plots for other fluids such as Freon (ref. 13) and water (ref. 14). There are a number of interesting features in this figure. First, it is obvious that there is a very steep portion of the heating curves (labeled A) associated with nucleate boiling. The level of the temperature difference associated with nucleate boiling is a function of pressure; the ΔT decreases with increasing pressure. Further, there is a film-boiling region (labeled B) that extends over a wide range of heat fluxes and driving temperatures. No physical burnout conditions were encountered over the range presented in this figure. At the higher driving temperatures, the film-boiling and supercritical data tend to merge into one band. Apparently, the mechanisms for the heat transport are similar for both fluid states.

Associated with the development of the boiling curves was an observable hysteresis phenomenon that influenced the data points in transition from nucleate to film boiling. The hysteresis effect did enable more data to be gathered in the transition region between nucleate and film boiling. When the heat flux was being increased during the test procedure, a discontinuous jump from the nucleate to film-boiling region took place. This is not to imply that a true discontinuity in the boiling curve exists. The jump occurred because heat flux and not wall temperature was the controlled variable. By gradually decreasing heat flux, data points within the gap could be obtained, and many of these appear in this figure.

A discussion of the nucleate portion of the curve shows that only a small driving temperature is required for the nucleate boiling of

hydrogen. The magnitude is comparable to what other investigators have found (refs. 1 to 3). For saturated water, the driving temperature in nucleate boiling is one order of magnitude higher. The pressure level, or proximity to critical pressure, has a pronounced effect on the nucleate portion of the boiling curve. As the pressure level approaches the critical value (from the low side) the maximum heat flux associated with the nucleate-boiling curve reduces, until at or near critical pressure there is no steep-sloped nucleate curve. Since the heat of vaporization of hydrogen diminishes with increasing pressure, it may be postulated that the enhanced heat-transfer rate in the nucleate regime is related to the evaporation process. There is still a running argument as to whether evaporation or the stirring action of bubbles control the enhancement of heat transfer in nucleate boiling. These hydrogen data seem to corroborate recent reports (refs. 15 and 16) that emphasize the importance of evaporation.

Effect of Subcooling on Boiling Curve

Although it was difficult to achieve steady-state experimental conditions with subcooling, some subcooling data in Earth gravity was obtained. The maximum subcooling was of the order of 5° R. Nevertheless, this small amount of subcooling sponsored appreciable changes in the nucleate boiling curve as is shown in figure 3. Such a shift in the curve toward higher temperature differences would be expected from nucleation theory (ref. 17) or from the large amount of subcooled boiling data in the literature for other fluids. It can be concluded that the degree of subcooling is very important in controlling the nucleate-

boiling process (particularly incipience) in liquid hydrogen.

Multigravity Effects, Nucleate and Film Boiling

Figure 4 consists of two plots in which 7-g nucleate-boiling data are compared to Earth-gravity data at two saturation conditions of 52 and 90 pounds per square inch absolute. The comparative 1-g and 7-g runs were made sequentially and, considerable care was exercised in making the thermodynamic conditions similar. Tank pressure and fluid temperature were carefully monitored before data were taken.

Actually there are three separate heating curves on each plot in figure 4 all of which were generated by incrementally increasing the heat flux. The experimental procedure is significant to an interpretation of the comparative data on these plots. First, the Earth-gravity data (curve A) were obtained using a freshly filled Dewar. The hydrogen Dewar was refilled with fresh fluid and the initial thermodynamic conditions were reproduced, then the multigravity curve (curve B) was generated. Finally, curve C is a multigravity repeat that followed immediately after the generation of curve B by using the same hydrogen fill.

A comparison of curves A and B on each plot shows that there is definite movement of the nucleate incipience conditions to a somewhat higher ΔT . These multigravity curves also show a steeper slope of the nucleate curve. As is seen in the figures, curve B generally crosses the 1-g curve and thereafter remains somewhat higher than the 1-g curve. It does appear that the upper limit of nucleate boiling is at a somewhat higher heat flux for the multigravity case.

An immediate repetition of the multigravity curve leads to a different curve, particularly at the low heat flux and where incipience

begins. Perhaps this can be explained by arguments similar to those proffered in the hysteresis discussion, in which it was pointed out that the history of the thermal layer influences the boiling mechanism. It should be noted that curve B was generated with a newly loaded Dewar of hydrogen. No previous thermal heating of the boundary layer had occurred; thus the boiling data represent conditions with a virgin thermal layer. In contrast, the data for curve C were taken immediately after those of curve B, and it is probable that some residue of the previous thermal layer remained, as well as the possibility of some vapor nuclei. Also, some heat could have been stored in the bakelite block. Thus, it did not take much driving temperature to initiate nucleation. It is interesting to observe that curves B and C become one curve at the higher heat fluxes.

It can be concluded from figure 4 that a multigravity environment can shift the incipience point of nucleate boiling, but once the boiling has been established the body-force environment does not greatly affect the boiling curve. (There is little spread in the ΔT data for both 1-g and multigravity data.) This has been confirmed in figure 5, which includes 3-g and 10-g data.

It has also been learned that the boundary-layer history markedly influences the boiling curve in the vicinity of the incipience point. Thus, it may be concluded that the history and condition of the thermal layer is as significant as the body-force effect in controlling nucleate-boiling incipience. This observation is consonant with what has been observed with subcooling and the hysteresis-phenomenon effects.

In figures 4 and 5, the upper end of the nucleate curve occurs at a higher heat flux for the multigravity data than for the 1-g data. This indicates that free convection is becoming important in this region of the boiling curve.

A much more definite body-force effect on film boiling was noted. Figure 6 shows a comparison of 1-g and 7-g data in the film-boiling region. The associated nucleate data are shown for comparative purposes. The 7-g data are consistently about 12 to 15 percent above the 1-g data. In obtaining these data, both increasing and decreasing heat flux experimental procedures were used. Regardless of which procedure was used, the data are reproducible. Decreasing the heat flux did enable some transition points to be obtained that could not be obtained otherwise. A hysteresis phenomenon in the transition region was observed.

The principle observation to be made from figure 6 is that there is a definite gravity effect on the film-boiling region and this was not observed in the established nucleate region.

Multigravity Effects on Supercritical Heating

Figure 7 is a comparison of 1-g and 7-g heat-transfer data for supercritical pressures. The data include two pressures, 215 and 260 pounds per square inch absolute. Regardless of the pressure level, the data can be grouped into two distinct bands, Earth gravity and multigravity, with the latter being above the former. Assuming some sort of free-convection correlation involving a Rayleigh number, this trend would be expected. Furthermore, in free-convection correlations, the exponent on the Rayleigh number may range anywhere from approximately

0.25 to 0.35. Consequently, the ratio of the multigravity heat flux to the Earth-gravity heat flux should be

$$\frac{q_{ng}}{q_{1g}} = (n)^{0.25 \text{ to } 0.35} \quad (1)$$

where q is the heat flux, and n is the number of g 's imposed. The ratio of the heat fluxes from figure 7 appears to be about 1.65. thus the exponent of n would be approximately 0.26. This is within the range of values cited for free convection. Thus, it may be concluded that the supercritical heating of hydrogen in multigravity may be predicted from a standard free-convection correlation by using 1- g data as a reference situation.

Supercritical Heating Mechanism

It has been noted already from figure 2 that the supercritical heating data fall along a fairly linear band (on a log-log plot of q against ΔT). This is similar to what would be observed for the free convection of any fluid. No hysteresis or apparent dependence on experimental procedural technique was encountered in getting data that would group within a narrow band.

Visual studies of the supercritical regime showed that a phenomenon somewhat resembling columnar boiling was at work. Of course, bubbles were not present but sizable agglomerations of low-density molecules were rising through a denser and colder fluid. This gave a boiling-like appearance to the heating process.

This boiling-like mechanism for a supercritical fluid has been observed by Griffith and Sabersky (ref. 13) in high-speed photographs of

Freon. Also, the possibility of such a mechanism was postulated in a prepared discussion by Goldmann in reference 18. The mechanism was postulated to explain the enhanced heat transfer near the critical point.

SUMMARY OF RESULTS AND CONCLUSIONS

1. The heating curves (heat flux against temperature potential) for liquid hydrogen in the subcritical and supercritical pressure states are similar to curves for other fluids. In the subcritical state, nucleate and film-boiling regions are clearly indicated. The upper limit of the nucleate curve is pressure dependent. The film-boiling and supercritical heating curves tend toward coincidence at high heat fluxes.
2. The nucleate portion of the subcritical heating curve is sensitive to subcooling and hysteresis effects. With the exception of bubble incipience, very little influence of multigravity effects was noted on the curve. There probably is some tendency for the upper limit of nucleate-boiling heat flux to shift upward as gravity is increased.
3. No hysteresis effects were noted in the established film-boiling region of the boiling curve. A definite hysteresis phenomenon was noted, however, in the transition region between nucleate and film boiling. In fact, certain operating points could only be achieved by approaching from a high to a low heat flux. In the established film-boiling region, changing the gravity environment from 1 to 7 g's produced a 12- to 15-percent increase in the heat flux.
4. It is also concluded that the mechanisms of heat transport for established film boiling and supercritical heating are similar. The high-speed photographic evidence of rising columns of low-density

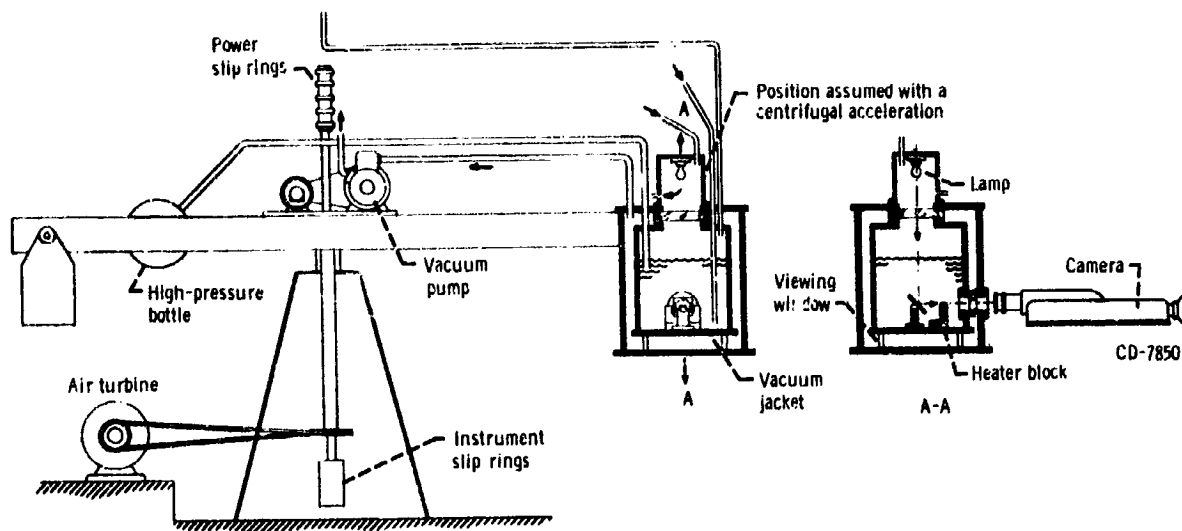
agglomerates and the heat-transfer data support this conclusion. This similarity also supports the view that free convection is the primary mechanism in the film-boiling region. The gravitational dependence of the supercritical data followed the Rayleigh number (free convection) prediction.

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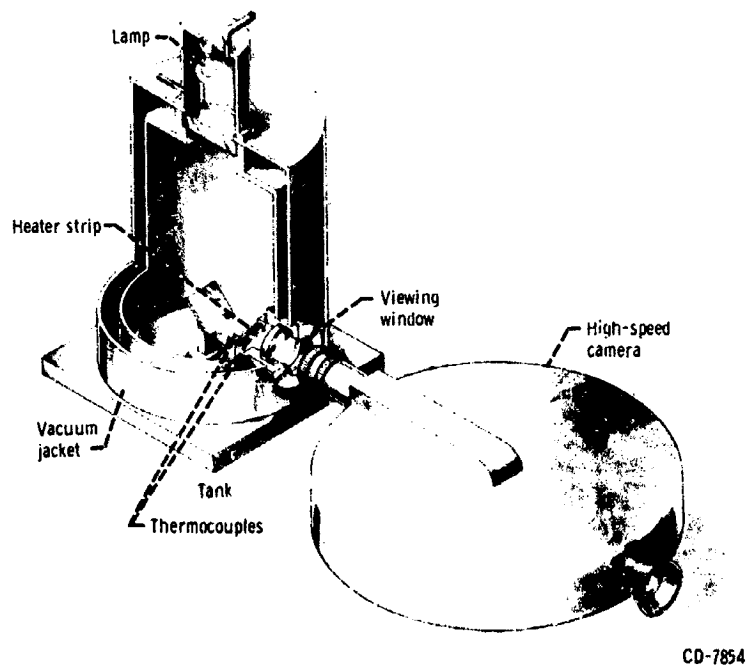
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(Discussion by K. Goldmann, p. 84.)



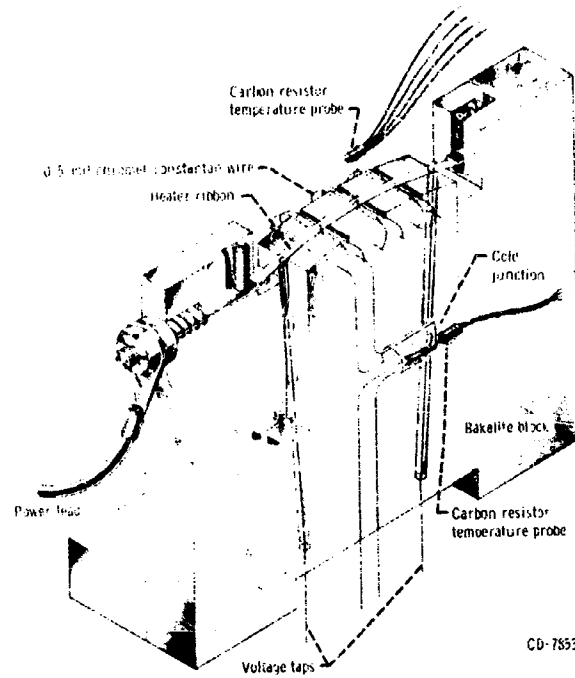
(a) Centrifuge assembly.

Figure 1. - Centrifuge apparatus.



(b) Tank and camera assembly.

Figure 1. - Continued, Centrifuge apparatus.



(c) Heater block construction and instrumentation.

Figure 1. - Concluded. Centrifuge apparatus.

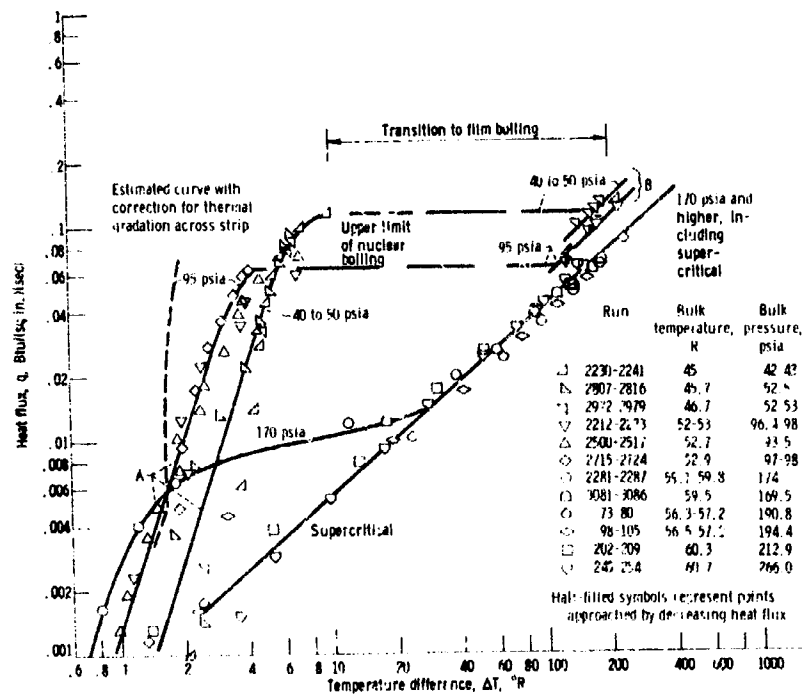


Figure 2. Heating curve for subcritical (saturated) and supercritical para-hydrogen at Earth gravity (sensing thermocouple underneath heater ribbon).

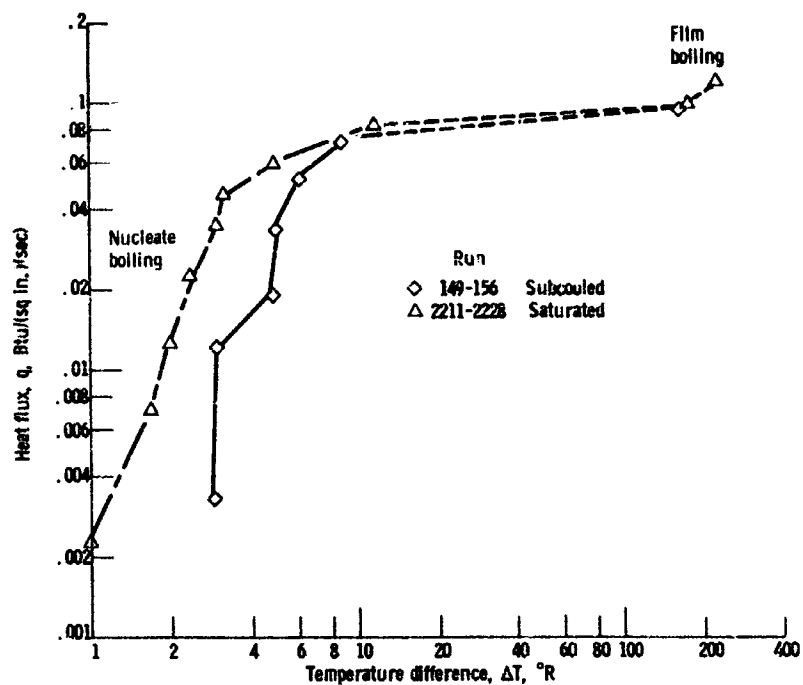


Figure 3. - Effect of subcooling on boiling curve for para-hydrogen at Earth gravity. Pressure, 97 pounds per square inch absolute.

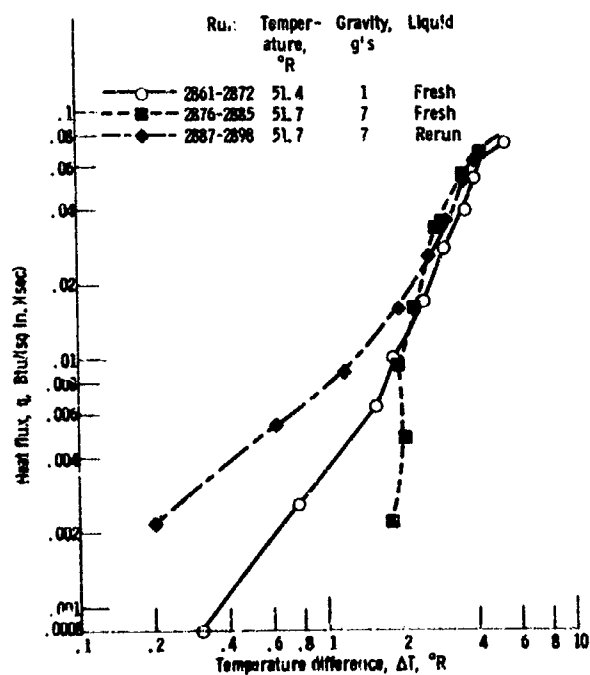


Figure 4. - Effect of multigravity accelerations on nucleate boiling for saturated para-hydrogen. Pressure, 91 pounds per square inch absolute.

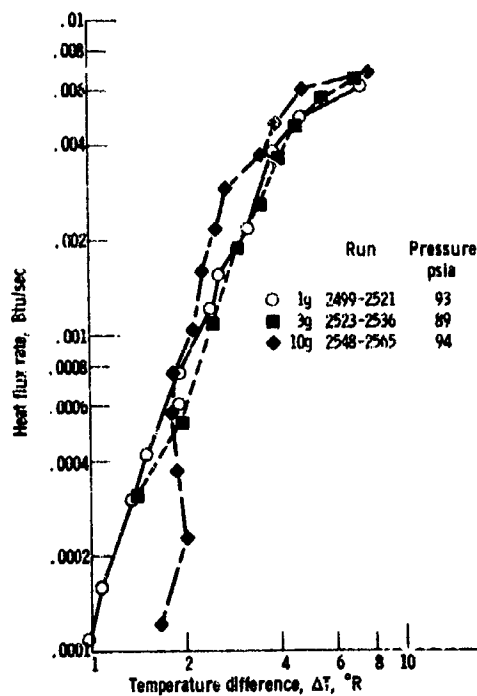


Figure 5. - Effect of multigravity accelerations on nucleate boiling for para-hydrogen.

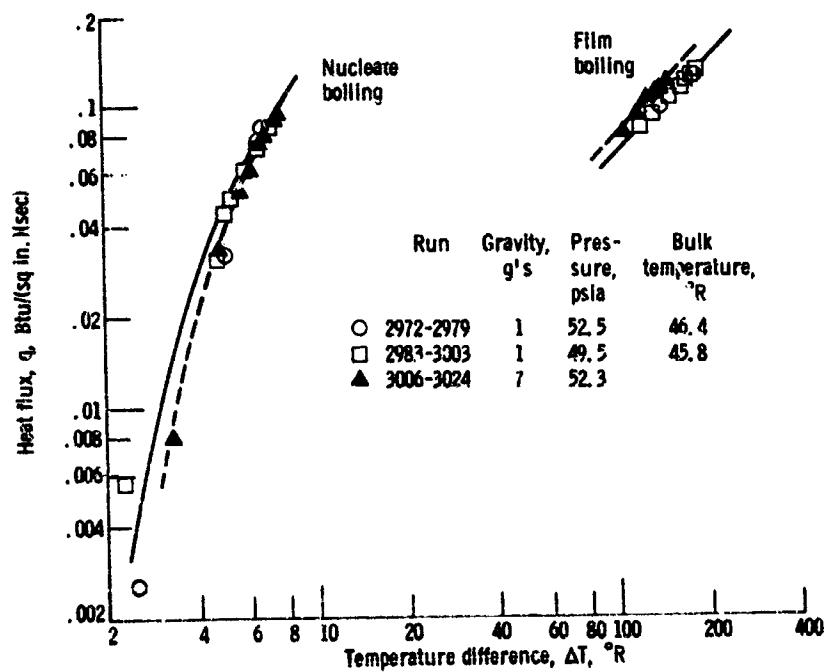


Figure 6. - Comparison of effects of acceleration on nucleate and film boiling for para-hydrogen.

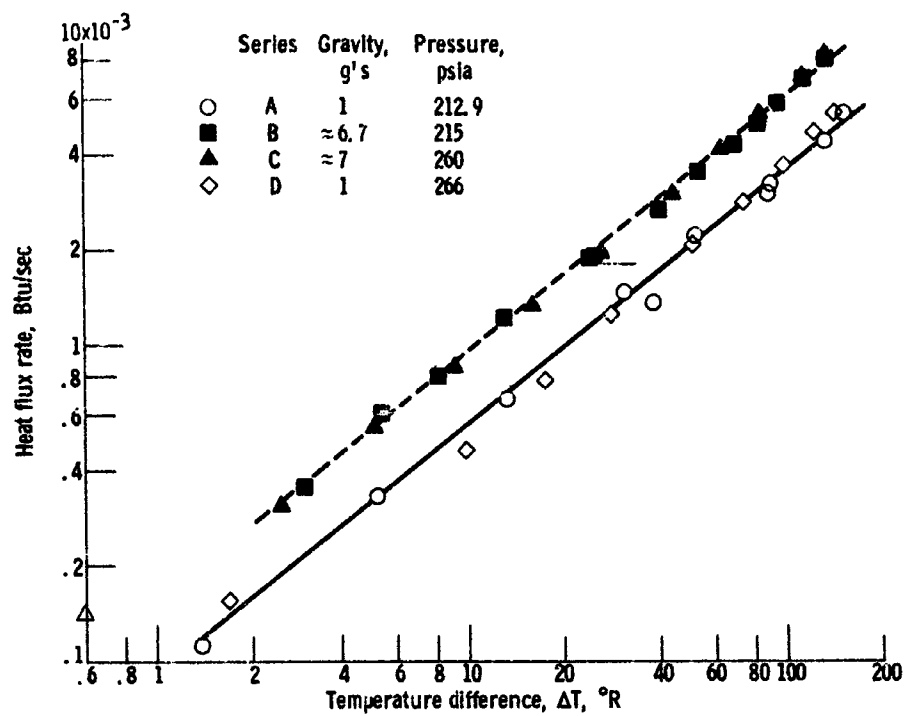


Figure 7. - Effect of multigravity accelerations on supercritical heating for para-hydrogen.